(12) UK Patent Application (19) GB (11) 2 174 505 A

(43) Application published 5 Nov 1986

(21) Application No 8511425

(22) Date of filing 4 May 1985

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(51) INT CL[4]
G02F 1/01

(52) Domestic classification (Edition H):
G2F 21X 23F 25M2 26X 28C 28W CW
U1S 2139 2203 G2F

(56) Documents cited
None

(58) Field of search
G2F
Selected US specifications from IPC sub-class G02F

(54) Optical signal processing

(57) The phase of modulation of an optical signal (P_{in}), in particular intensity modulation, is controlled to a predetermined value by applying the signal in a predetermined power split ratio to an unbalanced fibre Mach Zehnder interferometer (10) which is sure that the signals applied to its output coupler (13) are in-phase and quadrature (I, Q), the phase of the output signal $P_{out\,1}$ being determined by the power split ratio. The predetermined power split ratio is achieved by causing an appropriate optical phase difference between the optical signals in the arms (3, 4) of fibre Mach Zehnder interferometer (1). If required the amplitude of the phase controlled $P_{out\,1}$ signal can be controlled by a third fibre Mach Zehnder interferometer (17).

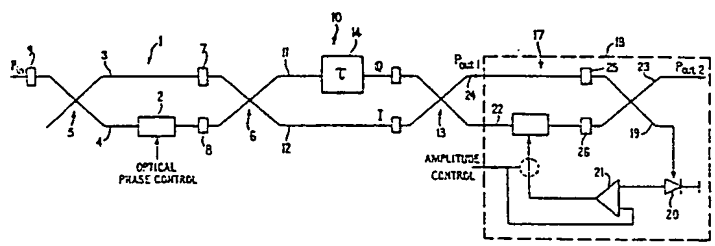

FIG.1

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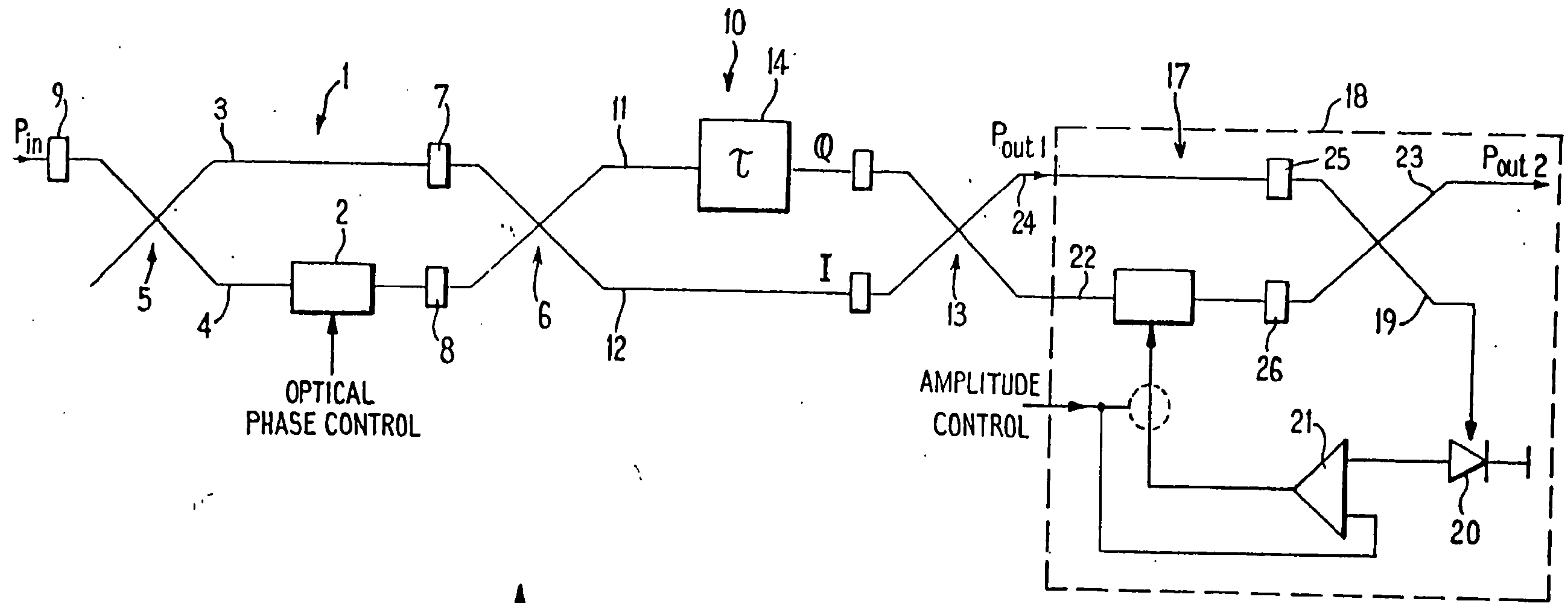
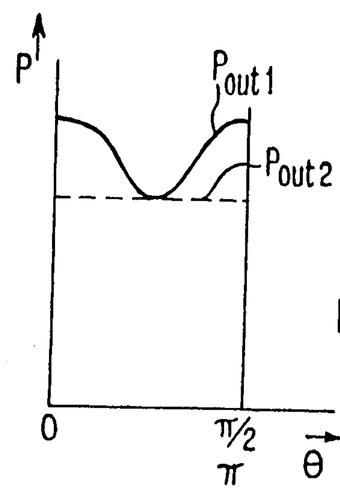
The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.



P_in
9
5
3
4
1
2
OPTICAL
PHASE CONTROL
7
8
6
11
12
10
14
τ
Q
I
13
P_out 1
24
22
17
18
25
26
23
P_out 2
19
AMPLITUDE
CONTROL
21
20

FIG.1



P
P_out 1
P_out 2
0
π/2
π
θ

FIG.2

SPECIFICATION

Optical signal processing

This invention relates to optical signal processing and in particular, but not exclusively, to the control of the phase of an intensity modulated signal.

In phased array radar systems there are a matrix of antenna elements which are driven at microwave frequencies with different phase relationships for steering of the antenna. If there are a large number of antenna elements there are practical problems associated with the separate waveguides required for all the different antenna elements. Optical beam steering phased array systems have thus been suggested since they require only a single microwave power feed and a plurality of optical fibres. One arrangement requires that a light source is intensity modulated at microwave frequencies and its phase be electrically controllable. Various solutions have already been proposed, many requiring sophisticated integrated optic technology.

According to one aspect of the present invention there is provided a method of controlling the phase of modulation of an optical signal by means of first and second fibre Mach Zehnder interferometers arranged in series, the method comprising the steps of applying the modulated optical signal to the first interferometer, operating the first interferometer whereby to obtain a predetermined power split ratio between the optical signals applied to the second interferometer, and causing the optical signals applied to the output coupler of the second interferometer to be in-phase and quadrature respectively, the output of said coupler being at a phase determined by the predetermined power split ratio.

According to another aspect of the present invention there is provided apparatus for controlling the phase of modulation of an optical signal comprising first and second fibre Mach Zehnder interferometers arranged in series, the first interferometer being such that in use an input modulated optical signal is supplied thereby to the inputs of second interferometer with a predetermined power split ratio therebetween, and the second interferometer being such that the optical signals applied to its output coupler are in-phase and quadrature and the output of the coupler is at a phase determined by the predetermined power split ratio.

Embodiments of the invention will now be described with reference to the accompanying drawings, in which:

Figure 1 illustrates schematically a series arrangement of three fibre Mach Zehnder interferometers, and

Figure 2 illustrates variations in output signal amplitude with phase.

As mentioned above the conventional optical beam steering phased array radar systems typically employ integrated optic technology. The solution we propose however is capable of being implemented using optical fibre based components. This has the advantage of low loss. The fibre itself is very low loss and fibre to fibre interfaces have very low loss when compared with interfacing to other material technologies. An additional advantage is that the techniques proposed are all realisable now.

The proposed method makes use of the well known "I and Q" technique for producing any desired phase shift by summing two components of a signal which are of different amplitude and in-phase and quadrature, respectively, the phase shift achieved being dependent on the ratio of the splitting of the signal power between the two components. In an optical beam steering phased array radar system application of the method, although this is not the only possible application, the system operates at a high modulation frequency (~10GHz) but it is only required to operate over a small frequency range (fractional bandwidth) so that the provision of a 90° ($\pi/2$) phase shift to achieve the in-phase and quadrature components may be achieved by the introduction of an optical delay line. The remaining problems are how to provide an electrically variable coupling ratio and how to combine the delayed and undelayed (in-phase and quadrature) signals without producing undesirable optical interference at this point. It is undesirable as small fractional changes in optical frequency could cause larger fluctuations in the output signal and such frequency fluctuations may be unavoidable.

We propose that the variable ratio (power split variation) is provided by a balanced path length optical fibre Mach Zehnder interferometer 1 (balanced interferometer) (Figure 1) with an optical phase shift control 2 in one (as illustrated), or both, of the fibre arms 3 and 4. Optical power P_{in} is input to one port of a coupler/combiner 5 by for example intensity modulating at microwave frequencies the output of a light source (not shown), for example a semiconductor laser. A π change in optical phase between the two fibre arms of the interferometer will cause the output to move from one output port to the other of an output coupler/combiner 6, and any ratio of power split may be obtained by intermediate values of optical phase shift. The balance requirements are, firstly, that the delay difference between the fibre arms is less than the source coherence time, if not then incomplete extinction will occur, limiting the range of split ratios that can be obtained, and, secondly, that the delay difference be sufficiently small that unwanted fluctuations in source frequency should cause negligible intensity noise in the output. An unbalanced interferometer is a frequency discriminator or FM to AM converter with sensitivity proportional to path difference.

There is an additional requirement that the polarisation states at the output coupler/combiner 6 be identified, otherwise this too will limit the possible extinction and range of split ratios. This requirement may be met be the inclusion of a respective polarisation controller 7 and 8 in each of the fibre arms 3 and 4. If it is not possible to maintain extinction for any input state of polarisation, then an additional polarisation controller 9 may be employed at the input to pre-adjust the input state.

The necessary optical phase control is achieved by a corresponding change in optical path length of the fibre arm 4. This may be provided by a conventional piezo-electric fibre stretcher, such as a PZT modula-

tor for example winding fibre around a PZT cylinder for controlling phase a large amount, or glueing a fibre onto a PZT disc for a small amount. Any method which results in stretching of the fibre in response to an electrical signal may be employed, another example being the use of magnetostrictive materials and bonding the fibre to a strip thereof.

The aforementioned delaying of one optical signal component and combining of the resultant inphase and quadrature optical signals is achieved by means of an unbalanced optical fibre Mach Zehnder interferometer 10. The delay difference may easily be achieved by use of different lengths of fibres in the arms 11 and 12 between the couplers 6 and 13. This may be fine tuned if desired by heating and stretching one or other of the fibres to ensure that the combining coupler 13 is accurately fed with inphase (I) and quadrature (Q) components.

In Figure 1 the delay (τ) is indicated by a component 14, which may for example add an extra 20 or 30cm of fibre. In the interferometer 10 the optical signals are required to be combined incoherently. This may be achieved by either or both of the following two ways. The first way involves ensuring that the states of polarisation of the two signals to be combined are orthogonal. This can be achieved using polarisation controllers 15 and 16 in the fibre arms. Alternatively, if high birefringence (polarisation maintaining) fibre is used, then the polarisation controllers may be omitted, but it is necessary to couple the light source into a principle axis of the fibre, and it is necessary to ensure, for example, by fibre joint rotation, that the axes are aligned for interferometer 1 and orthogonal for interferometer 10. The second way is by ensuring that there is minimum mutual optical coherence between the two signals to be combined. This can be achieved by using a source with a coherence time significantly less than the delay τ or by using a multimode source such that τ falls between coherence peaks. Another possibility is to intensity modulate the source to produce pulses of length less than τ and spacing greater than τ, thus ensuring zero coherence over a delay of τ.

The overall system including interferometers 1 and 10 requires modulation with a period of 4 τ if the effect required (phase control of the intensity modulated optical signal) is to be obtained with an intensity modulation waveform whose duty cycle is less than 25% with full extinction. Subsequent electrical filtering of the output would eliminate all except the wanted fundamental component.

The system described so far enables the phase of the intensity modulated optical signal to be fully controlled, however, the output signal amplitude will vary from a maximum at 0° and 90° phase shift, to a minimum of $1/\sqrt{2}$ of the maximum at 45° since inphase and quadrature components are being added (see Figure 2). If this amplitude variation is too great it may be made negligible for example either by controlling the source modulation depth to compensate or by introducing a third optical fibre Mach Zehnder interferometer (balanced) 17 which can be used to control the output amplitude by operation in a similar manner to the interferometer 1. The interferometer 17 is part of a mean power control loop indicated within dashed box 18. The power output from one port 19 of interferometer 17 is detected by detector 20 and amplified by differential amplifier 21 whose output is employed to control the optical phase of the optical signal in arm 22 and thus the relative splitting between the two output parts 23 and 19. Figure 2 illustrates the power outputs $P_{out\,1}$ and $P_{out\,2}$ at ports 24 and 23, respectively, versus phase shift θ. The abscissa is 0 to $\pi/2$ for r.f. phase or 0 to π for optical phase (in interferometer 1). If polarisation controllers are employed in interferometers 1 and 10 they will also be required in interferometer 17 as indicated at 25 and 26. The interferometer 17, enables the output power to be held constant and also for it to be controlled, if so desired.

The operation of the system comprising interferometers 1 and 10 can be summarised as follows. The input coupler 5 serves to split the intensity modulated optical power input P_{in} into two components which each pass along a respective one of the fibre arms 3 and 4 of interferometer 1. Depending on the electrical signal applied to the PZT modulator 2 a change in optical phase between optical signals in fibre arms 3 and 4 is achieved, with corresponding changes in how the optical power is split between the fibre arms of interferometer 10. In one phase condition all power will pass along one fibre, in another all power will pass along the other fibre and in an intermediate phase condition the power will be split 50% along each line. The component 14 then introduces a delay into the one optical signal passing along that line so that the optical signals at the output end of interferometer are then of different power, one in-phase and one in quadrature. Thus by controlling the optical phase at interferometer 1 one can control the phase (electrical) of the output intensity modulated optical signal.

Whereas the above description is concerned with controlling the phase of intensity modulation of an optical signal the arrangement may be employed to control the phase of any form of modulation.

CLAIMS

1. A method of controlling the phase of modulation of an optical signal by means of first and second fibre Mach Zehnder interferometers arranged in series, the method comprising the steps of applying the modulated optical signal to the first interferometer, operating the first interferometer whereby to obtain a predetermined power split ratio between the optical signals applied to the second interferometer, and causing the optical signals applied to the output coupler of the second interferometer to be in-phase and quadrature respectively, the output of said coupler being at a phase determined by the predetermined power split ratio.

2. A method as claimed in claim 1 wherein the phase of intensity modulation of the optical signal is controlled.

3. A method as claimed in claim 2 wherein the operation of the first interferometer comprises adjusting the relative optical phase of the optical signal

portions in the two arms of the interferometer.

4. A method as claimed in claim 3 wherein the first interferometer is balanced and the relative optical phase is adjusted by stretching one of the fibre arms of the first interferometer.

5. A method as claimed in claim 4, wherein the stretching is achieved by a PZT modulator.

6. A method as claimed in any one of claims 2 to 5, wherein the step of causing the optical signals to be in-phase and quadrature comprises delaying the optical signal in one arm of the second interferometer.

7. A method as claimed in claim 6 wherein the second interferometer is unbalanced and the delay is obtained by virtue of an optical delay line comprising an extra length of fibre in the one arm.

8. A method as claimed in any one of claims 2 to 7 and wherein polarisation controllers are disposed in both fibre arms adjacent to the output couplers of both the first and second interferometers.

9. A method as claimed in any one of claims 2 to 8 including the step of controlling the amplitude of the phase controlled intensity modulated optical signal.

10. A method as claimed in claim 9 wherein the amplitude controlling step comprises applying the output of the second interferometer to a third, balanced, fibre Mach Zehnder interferometer and operating the third interferometer whereby to control the amplitude in a predetermined manner.

11. A method as claimed in claim 2 wherein the second interferometer is unbalanced and wherein to suppress coherent interference at its output coupler the optical signal portions applied thereto are caused to be of orthogonal polarisations.

12. Apparatus for controlling the phase of modulation of an optical signal comprising first and second fibre Mach Zehnder interferometers arranged in series, the first interferometer being such that in use an input modulated optical signal is supplied thereby to the inputs of second interferometer with a predetermined power split ratio therebetween, and the second interferometer being such that the optical signals applied to its output coupler are in-phase and quadrature and the output of the coupler is at a phase determined by the predetermined power split ratio.

13. Apparatus as claimed in claim 12 and for controlling the phase of intensity modulation of the optical signal.

14. Apparatus as claimed in claim 13 wherein the first interferometer includes means to control the relative optical phase between the signals in its arms and thus the power split ratio.

15. Apparatus as claimed in claim 13 or claim 14 wherein the second interferometer includes an optical delay line in one arm whereby to provide the quadrature optical signal.

16. Apparatus as claimed in claim 15 wherein the second interferometer is unbalanced and the optical delay line comprises an extra length of fibre in the one arm.

17. Apparatus as claimed in claim 13 wherein the second interferometer is unbalanced and wherein to suppress coherent interference at its output coupler means are provided whereby the optical signal portions applied thereto are of orthogonal polarisations.

18. Apparatus as claimed in any one of claims 13 to 17, further including means to control the amplitude of the phase controlled intensity modulated optical signal.

19. Apparatus as claimed in claim 18 wherein said amplitude controlling means comprises a third fibre Mach Zehnder interferometer in series with the second interferometer.

20. A method of controlling the phase of intensity modulation of an optical signal substantially as herein described with reference to the accompanying drawings.

21. Apparatus for controlling the phase of intensity modulation of an optical signal substantially as herein described with reference to the accompanying drawings.

Printed in the UK for HMSO, D8818935, 9/86, 7102.
Published by The Patent Office, 25 Southampton Buildings, London, WC2A 1AY, from which copies may be obtained.